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Recommended Carbon Dioxide and Relative Humidity Levels for Maintaining Acceptable Indoor Air Quality

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At the request of the AFLC Surgeon, AFOEHL prepared a recommendation for carbon dioxide and relative humidity levels to maintain adequate indoor air quality. The report summarizes and analyzes the results of approximately 75 building investigations and makes recommendations for controlling indoor air quality by use of carbon dioxide levels. The report discusses the symptoms and signs found in occupants and the possible causes for same. A draft of this report was previously released under the title "Proposed Indoor Air Quality Standard for AFLC/SG," Oct 90 AFOEHL Report number 90-169CA00111KGA.

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Preface

The Air Force Occupational and Environmental Health Laboratory has been investigating indoor air quality complaints for four years. We have established a data base which includes measures of carbon dioxide, relative humidity, organic vapors, and physical agents and the symptoms associated with them. We have also measured fresh and total air flow rates in these facilities. As a result of our findings we have recommended indoor air quality standards for the Air Force and developed a standardized method of investigation and management of indoor air quality problems.

We will discuss our standard approach and our findings to date, including a trend analysis of the causes of indoor air quality complaints. Our approach consists of simultaneous assessments by a health care provider, public health officer and industrial hygienist. The protocol allows the complete assessment of most buildings in less than two days. The cornerstone of our method involves the use of a standardized questionnaire which is analyzed on site with the use of Epi Info software provided by CDC. We have found that the trend of a combination of symptoms relates to levels of carbon dioxide and relative humidity. Adjusting these levels usually eliminates the complaints. In the majority of instances we have not found chemical or biological sampling to be of any value. Eliminating these two requirements, except where symptoms warrant them, greatly decreases the cost and time involved in doing investigations.

Contents

I. INTRODUCTION

A. American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 62-1989 defines acceptable indoor air quality as, "Air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (ASHRAE Standard 62-1989, paragraph 3). This statement sets the air quality standard. The standard set is qualitative, that is, it is not dependent on any particular measured level of any substance. It defines acceptable air as that air which does not promote ill health and, beyond simply not causing illness, it must be acceptable to 80% or more of the population exposed. In another section, paragraph 6.1.3, the statement is made that "Comfort (odor) criteria are likely to be satisfied if the ventilation rate is set so that 1000 ppm CO_2 is not exceeded." We believe the standard as stated by ASHRAE is well done, and have no difference of opinion whatever with its goals and objectives - healthy, comfortable and productive human beings. The second statement is not standard setting. It is a statement of belief, based on engineering experience, that comfort criteria and odor criteria are likely to be met if the level of carbon dioxide is kept at about 1000 ppm. This statement does not reflect on health, nor does it set 1000 ppm as a criterion to be adhered to. It says it is a guide to be used as a rough measure of appropriate ventilation rates. A number this loosely set is not a definitive design criterion. It is with this number that we do not agree. We do not believe that health, comfort or optimum productivity are served when carbon dioxide is at that level. This report provides health, productivity and cost information which we believe justifies using ventilation rates which will keep the carbon dioxide level at 600 ppm or lower. It has been our experience that buildings run at 1000 ppm do not satisfy anything like 80% of the population. They appear to satisfy 20% or less. The purpose of this report is to refine the level of carbon dioxide used as a guide for adequate ventilation.

B. Indoor air quality has been a problem for centuries. The following quote is attributed to Benjamin Franklin by Woods and Morey.(1)

> "I considered (fresh air) an enemy, and closed with extreme care every crevice in the room I inhabited. Experience has convinced me of my error. I am persuaded that no common air from without is so unwholesome as the air within a close room that has been often breathed and not changed. You physicians have of late happily discovered, after a contrary opinion had prevailed some ages, that fresh and cool air does good to persons in the smallpox and other fevers. It is hoped that, in another century or two we may find out that it is not bad even for people in health."

The two centuries have passed. It is time for physicians to remember, and engineers and architects to learn the lesson that Franklin learned those centuries ago. Fresh air is good for people and stale air is bad. The result of poor air quality is lost productivity, and in some cases, frank illness among employees. It is estimated that the number of buildings affected by poor indoor air quality may be as high as 50% of all buildings and that these buildings effect 25% to 40% of all employed persons in the United States. This is a large public health problem.(3) Many heating, ventilating and air conditioning systems in the Air Force are presently reaching the end of their useful life. There is an immediate need for guidelines for air quality which can be used to estimate design and operational requirements so that we can purchase replacement equipment which will better meet our needs.

C. The indoor air quality (IAQ) problem has accelerated since the middle 1970s. The problem became noticeable coincident with the inception of the oil price induced energy conservation program. As a result of that program, design and operational parameters for ventilation have focused too narrowly on building temperature and energy consumption and not enough on providing both adequate air quality and comfort control. As the ASHRAE Standard states, engineering efforts should be used to optimize health, comfort and productivity factors. Only then can we know if energy is being appropriately consumed.

II. DISCUSSION

A. The recommended amount of outside air per person has fluctuated considerably over the years. Originally it was based on the amount of air necessary to control odor from human effluent. In the early 1900s, the recommendation was for 30 cubic feet per minute (cfm) per person of outside air depending on room volume. In the 1970s, energy based considerations drove the recommended rate of ventilation as low as 5 cfm. Apparently, it was forgotten that this rate had been shown to be too low to control odor.(22) The present standard published by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) calls for a minimum of 15 cfm per person. As noted above, it is also stated that a CO_2 level of 1000 ppm or lower is a guide, not a design criterion, to adequate ventilation. Higher rates are recommended by ASHRAE for conditions where air is poorly mixed in the interior space, or where unusual conditions exist. The standard appears to have been constructed on experience, the fact that the American Conference of Industrial Hygienists (ACGIH) published TLV for CO_2 is 5000 ppm, and engineering calculations based on mets as to what amount of CO_2 is produced by the average diet. No measured data or studies supporting the recommended 1000 ppm level appear to have been utilized. Without agreement as to what constitutes adequate air quality from a health, comfort, and productivity perspective, inappropriate focus on energy savings as the prime driving force behind air handler design and operation will continue. We propose using as guidelines consistently measurable human responses which can be interpreted as a disease, illness or sickness response to the environment. We also favor active use of the ASHRAE criterion of acceptability to 80% of the exposed population.

B. Many health standards are based on projections. The number of people made ill by high level exposure is projected by varying mechanisms to the low level exposure regime. The allowable exposure level is set at a number which coincides with a certain level of risk of acquiring disease. Generally, the allowable risk is set in the range of 1/100,000 to 1/10,000,000, risks far less than many commonly experienced risks in everyday life. This procedure may result in allowable exposure levels which are costly to attain and, in the view of some, questionable with regard to value in preventing disease. This approach was developed as the result of the discovery of chemicals, such as vinyl chloride, which were found to be carcinogenic at low levels of exposure. The method has the advantages of controlling irritant effects as well as decreasing the chance that any disease will result from the exposures allowed. Prior to this, standards were developed by setting levels which seemed reasonable based on current knowledge and lowering them if the need became apparent. The disadvantages of this method are that it tends to ignore irritant levels, and allows some measure of physiological change to take place providing the change is reversible. It assumes no permanent adverse effect has occurred as the result of the temporary physiological change, a fact which is sometimes not possible to know without long exposure histories. It does not prevent the occurrence of disease which may be caused by quantitatively low exposure levels. Indeed, it uses disease occurrence as a signal that change is needed. This method is still used in setting occupational exposure limits as the recent paper by Roach and Rappaport clearly shows.(21) Some middle ground is required between these extremes. The alternative we propose uses measurable health effects as the guide, and elimination of measurable effects as the goal. As health parameters we propose using any consistently measurable human response which can be interpreted as a disease, illness or sickness response to the environment. In this context the definitions of disease, illness and sickness are defined as follows:

1. Disease is any psychological/physiological change which results in an illness.

2. Illness is the subjective state of a person who is aware of not feeling well as the result of a physiological or psychological change.

3. Sickness is a state of social dysfunction. It is the role the individual assumes when ill.

For example, a cold results in physiological and psychological changes induced by the infecting organism. Awareness of the state of changed physiology constitutes the illness. The sickness is the change in behavior induced by the cold which results in the social consequence of reduced productivity. By analogy stale air generates physiological changes which result in sensations of fatigue and uncomfortable warmth. Awareness of the state of increased fatigue and warmth constitutes the illness. The persons expression of his/her subjective state and resulting loss of productivity is the sickness as seen from the social perspective. Based on the above definitions, this report will suggest indoor air quality guidance for current use. We hope it will serve as a catalyst for continuing refinement of these guidelines.

C. Building air quality problems can be categorized by origin of the source of the problem. NIOSH does this in a pamphlet entitled Indoor Air Quality, Selected References.(2) The following is a summary of their findings.

Total of 446 IAQ investigations

1. Inadequate Ventilation - 52%

   a. Insufficient fresh air

b. Poor air distribution and mixing

c. Draftiness and pressure differentials between office spaces

d. Temperature and humidity extremes and fluctuations

e. Improper or no maintenance on ventilation systems

2. Inside contamination - 17%

a. Chemicals from office machines such as copiers, signature machines and blueprint copiers

b. Improper use of pesticides and cleaning agents

3. Outside contamination - 11%

a. Improperly located exhausts and intakes resulting in

(1) Entrainment of exhaust air

(2) Intake of automobile exhaust

b. Odors and gases entering from sewers

c. Products from construction projects in the area

4. Microbiological contamination - 5%

a. Bacterial, fungal and protozoal products from the ventilation system and furnishings damaged by water

5. Building fabric contamination - 3%

a. Dermatitis from ventilation duct lining, glues and adhesives

b. Off-gassing of formaldehyde and other products from furnishings and building materials

The pamphlet concludes that there are three general categories of problems which are, with decreasing frequency, inadequate ventilation, chemical, and microbial contamination. Our experience, summarized below, is largely in agreement with that of NIOSH. We differ in that the NIOSH pamphlet, in the reprinted article by Dr Melius, et al, says they have not found any environmental measurement useful as an indicator of inadequate ventilation, but others have found CO_2 useful. We have found CO_2 to be a very useful indicator of the adequacy of ventilation.

D. Our Experience

1. The following information is drawn from surveys conducted by our organization over the past four years. These surveys were conducted to solve operational problems. This is a series in which the same people conducted the majority of the studies using the same techniques and equipment. Therefore,

the data has value as a case series study. Medical interviews were conducted in all cases. A standardized questionnaire was used in eight of the buildings. In the remainder, a standard medical interview was conducted. The discussion of our data reduction methods can be found in Appendix A. Based on this data reduction, we conclude that the symptoms of fatigue, drowsiness, feeling of temperature extremes, dizziness, increased ear, nose and throat problems are correlated with increased CO_2 and decreased humidity. Our analysis also indicates a tendency for increased headaches and problems breathing with increased CO_2 and decreased RH.

2. We use a model to clarify our observations. Our model is based on the following assumptions. First, there is a no effect threshold (A) for exposure to CO_2; second, there is an equilibrium constant established among the blood, lung and alveolar space (K); third, the maximum possible percentage of complaints is 100 percent; fourth, in a large enough sample there will always be an individual that experiences no symptoms. These assumptions produced the following model for predicting percentage complaints of fatigue based on measured CO_2 concentration;

$$\text{Complaints} = 100(1-e^{-(CO\ -A)K})$$

By using the SAS computer statistical software package, we found;

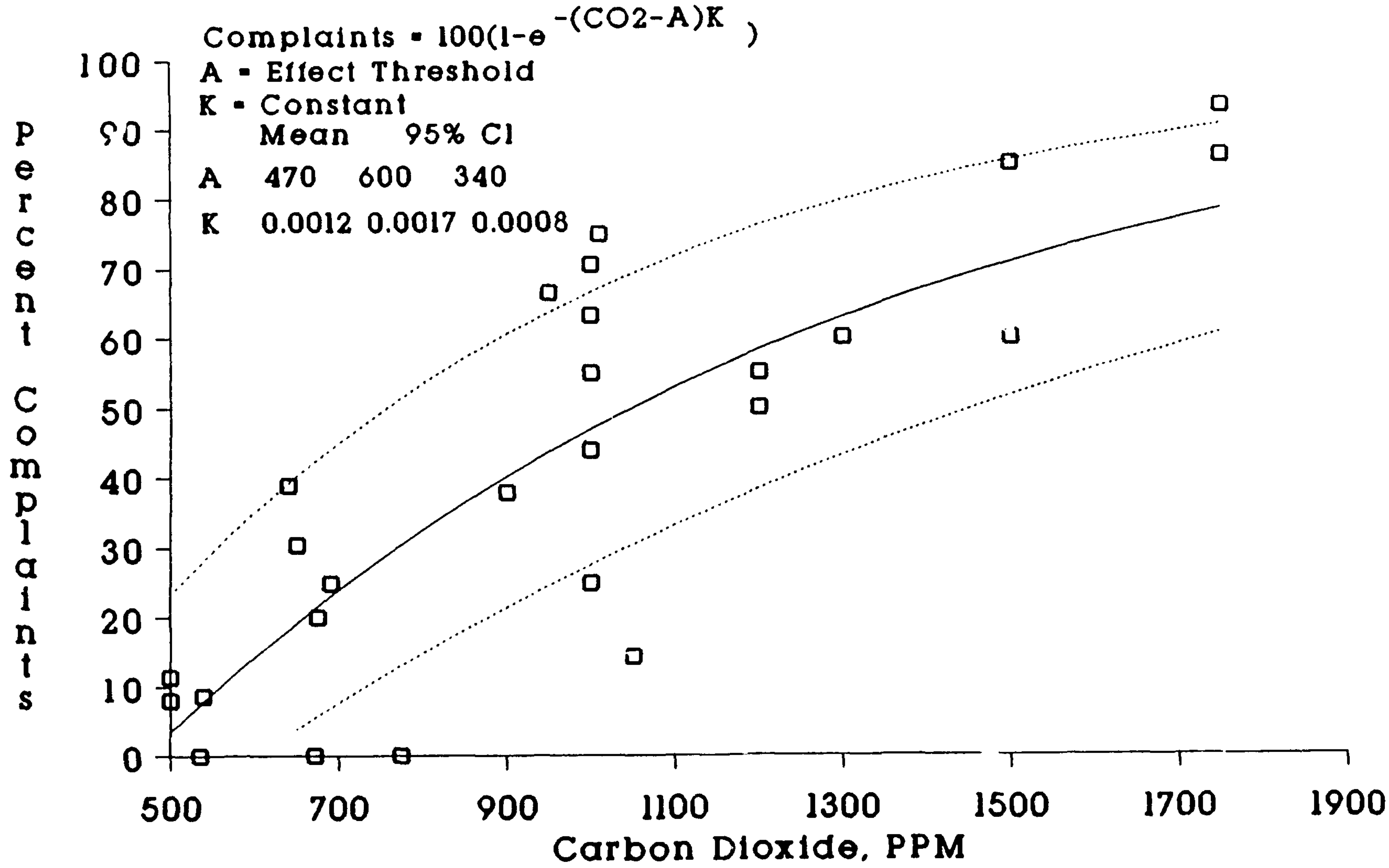
	Mean	95% confidence level	
A	470	600	340
K	0.0012	0.0017	0.0008

We conclude from this that at 600 ppm, some part of the population will experience some level of fatigue. This is in keeping with the findings of others.(8,24) The following Figure is a graph of this predictive model with our actual complaint rates at varying CO_2 levels superimposed.

E. The illnesses and symptoms resulting from IAQ problems are also discussed in the NIOSH pamphlet. NIOSH says, "... the symptoms and health complaints ...have been diverse and not specific to any particular diagnosis or readily associated with a causative agent. A typical spectrum of symptoms has included headaches, varying degrees of itching or burning eyes, irritations of the skin including rashes, sinus problems, dry and irritated throats and other respiratory irritations." The pamphlet also names allergies, humidifier fever, hypersensitivity pneumonitis, and conjunctivitis as diseases resulting from microbial contamination. Once again we have good agreement with NIOSH but would add aggravation of asthma and fatigue to the list. We also believe the symptoms are quite specific to the stimuli present. We believe the symptoms found in tight buildings in many cases are the direct result of RH outside the range of 40% to 65 , and CO_2 above 600 ppm. We begin the discussion with "human pollution" and CO_2.

1. Controlled tests of human dissatisfaction with air polluted by human effluent alone have given some interesting results.(19,20) People were exposed to air polluted only by human effluent and asked to give immediate judgments of the air quality. The judgments were based on a standardized adjectival questionnaire with a gamut reflecting satisfaction - dissatisfaction. The air was subjected to ventilation at a rate equivalent to

Percentage Complaints Related to CO2 Concentrations



21 cubic feet per minute per person (cfm/p) of 100% unpolluted air. The test situation was run for only 20 minutes when the test subjects were introduced and the judgments were made. Even with this high rate of fresh air, low human-only pollution loading and measuring only immediate response, 15% of the population found the air unacceptable. This makes it very unlikely that acceptable indoor air quality will be attained by air that is subjected to other sources of pollution as well as human pollution when a rate of 15 cfm/p or even 20 cfm/p is maintained. Moreover, many symptoms would not be apparent on immediate exposure. The CO_2 effects require time to become fully apparent as do many of the low RH effects. When CO_2 levels rise above 600 ppm the following symptoms will be experienced by building inhabitants with increasing intensity as the level climbs: sleepiness and fatigue; poor concentration; a sensation of stuffiness and awareness of breathing; a sense of increasing warmth even though temperature does not change. The intensity of the symptoms and the number of people experiencing them is correlated with the level of CO_2.

a. Both our own experience and that of others confirms this.(8,24) In general, between 15% and 33% of the population will have symptoms when the level is between 600 and 800 ppm. Between one-third and one-half become symptomatic between 800 and 1000 ppm, and virtually everyone will have some or all the symptoms when the level is above 1500 ppm. The sensation of increasing warmth has been shown to be related to CO_2 levels in a study which addressed the subjective response to changes in ventilation.(6) Effective temperature (ET) was held constant and the subject's appreciation of room temperature was gauged with a standard adjectival test ranging from minus four to plus four on a cool - warm gamut. There was an obvious, incremental increase in subjective temperature which correlated with increase in CO_2. The range of CO_2 involved was from 500 ppm to 1500 ppm. The sensitivity of the physiological response to low level CO_2 is made obvious by this study. A possible mechanism for this effect is vasodilation by CO_2. The temperature sensors in the skin would detect an increase in ter .rature due to increased peripheral blood flow through expanded capillary b js. The vasomotor and CO_2 respiratory control centers are close together and receive signals from many of the same areas of the brain and body at the same time. They are interrelated as well. There is little that will affect one that does not affect the other.

b. Undersea Biomedical Research published a supplement in 1979 which dealt extensively with physiological response to increased levels of CO . A number of interesting findings are detailed in this volume. The body takes less time to maximally adapt to high level CO_2 than to low level. With CO in the range of 3% to 20% adjustment takes five days. With CO_2 in the range from 1% to 1.5%, adjustment took three weeks.(7) The same article demonstrated a greater increase in measures of lung ventilation at concentrations of CO_2 in the range of 0.8% (8000 ppm) to 1% (10,000 ppm) than at 1.5% (15,000 ppm). Respiratory minute volume increased 37% when CO_2 was held at 1.5% for 42 days. Between days 1 and 24 the rate at 1.5% peaked at 39% and remained essentially unchanged thereafter. When the level was held between 0.8% and 1% the rate continued to rise for 56 days ending at 62%. In the 42 day time frame, it was at 52%. The increases were due to increases in tidal volume and not an increase in respiratory rate. The reason for this apparently reversed phenomenon is believed to be due to different adaptive mechanisms at higher and lower levels of CO_2. The speed of adaptation at high levels is believed to be due to buffering by bone calcium. The calcium is readily mobilized at the pH induced by the higher CO_2 levels. At lower levels the adaptation is due to kidney adjustment of ion excretion and absorption and by ventilation mechanisms. The kidney mechanism takes longer to develop effective control than the bone mechanism. The respiratory mechanism serves both an interim and supporting role. The author notes that ventilatory loading effects, though difficult to measure, continue below 2000 ppm.

c. Other sources (11) indicate that an increase in arterial CO_2 pressure of 1 mm Hg, the approximate equivalent of an added 1000 ppm of ambient CO_2, can increase the basal ventilation rate by 25%. The ambient level of CO_2 which will produce this effect will depend on where on the curve of alveolar and arterial CO_2 a given individual falls. Persons less well compensated by reason of disease or other consideration, and who are near, at or even above the higher end of the normal curve will respond at lower levels of additional CO_2. The normal range for alveolar CO_2 pressure is from 35 to 45 mm Hg. As with all such distributions, the upper one third will be more susceptible to effects, the lower third will be resistant and the remainder will fall in the middle. This may well account for the distribution of subjective effects found in tight buildings as CO_2 rises. CO_2 has other effects which must be considered. Two studies (9,10) show that kidney calcification and ultra-structural lung changes, the latter persisting at least four weeks post experiment, were present in animals when CO_2 was held constant at 1% (10,000 ppm). The lung changes disappeared when studies were done holding CO_2 at 5000 ppm. The kidney calcification remained a problem. Plasma calcium also continued significantly elevated at 5000 ppm.

d. Normally, our least conservative method for risk reduction uses the no observable effect level and divides that concentration by at least ten to obtain a level which will have no effect. Were we to do this with CO_2, we would set a TLV no greater than 500 ppm, one-tenth of the current level. Such considerations can help bring CO_2 into perspective with other substances we regulate. While it is true we encounter CO_2 everyday, it serves many physiological functions. Relatively small changes in body concentration rapidly bring about efforts at compensation. It should not surprise anyone that small changes produce detectable effects. Other stimuli to respiration are present in the average office environment. Anxiety is frequently present. It is usually generated by not knowing what is causing the symptoms and the almost invariable conflict between those managing the air handler and the building occupants. Frequently, it is believed that the problem is being caused by some unknown chemical toxin in the environment. Anxiety activates the as yet incompletely defined cortical respiratory drivers. These are very efficient and can increase basal respiratory minute volume as much as 12 times. Increased temperature causes an increase in the activity of the respiratory center. Irritative effects from accumulated dust, body effluents and ambient chemicals also affect respiratory minute volume. Some have suggested that the fact that submarines can operate at 8000 to 10,000 ppm should make it permissible for buildings to operate at 1000 ppm. We believe the analogy to be odious. Given that soldiers engaged in trench warfare can live in trenches for months, should we all rush out and dig trenches for our employees on the basis that it costs less than constructing a building? We could save a lot of construction and energy costs that way. Considering the youth, good health and mission of the average submariner and the wide variation in the health, age and mission of people in public buildings, we believe the subject warrants no further discussion. If the building is too warm, the air too dry, and the CO_2 too high, sensations of stuffiness, difficulty breathing and fatigue are not hard to understand.

2. The level of CO_2 reflects air change rates in the building. Therefore it is a relative measure of the increase in concentration of all effluents in the building which are produced at a steady rate. The opportunity for odorants to increase in an underventilated environment is obvious. The sense of smell is extremely sensitive. It functions primarily as a go, no-go system when compared to other senses. The detection level for some substances is below the part per billion range. The increase in concentration necessary to maximize response is as little as ten times threshold. This means that a barely perceptible odor at one part per billion becomes overwhelming at one part per hundred million. This is in marked contrast to the range covered by other senses. The eye has a range of 500,000 to one and the ear a trillion to one.(11) Odors were the original reason for ventilation standards. Smell has heavy emotional loading. Many times strong odors are the triggering agent for severe problems both in and out of buildings.(12-18) The literature in bibliography item 12-18 describes mass psychogenic illnesses. In all cases there was some pre-existing source of tension. The literature is replete with examples of individuals who have had similar symptoms established on a chronic basis due to a one-time exposure to odorants. Reference 21 describes some of these cases. Anyone who has been involved in IAQ problems is fully aware of the tremendous tension these problems can cause, not only between management and employees, but among employees as well. Psychological responses are a fact of life. We all have them every day. When tension is high, suspicion is high. The external environment is sifted in detail. People become more aware of their own bodies. Events that might otherwise be ignored may be endowed with meanings they do not possess. This is not a minor detail in the cost of these events. The effect that this has on morale and productivity is large as some of the more extreme cases in the references make readily apparent. These are normal responses. The responses are never the cause. The cause is whatever is causing the underlying tension. The responses are merely triggered by some event, often an odor. In our experience, there is always an element of these symptoms present in IAQ situations; however, it is never the cause of the problem. The symptoms in IAQ situations are real and are responses to real conditions in the building. The responses that can be classed as resulting from misinterpretation of bodily sensations are real and are responses to the often tense social environment of the workplace.

3. In our experience, the symptoms which result from low RH are: dry and sore nose and throat; bleeding nose, sinus and tracheal irritation, dry scratchy eyes, inability to wear contact lenses; and dry, itchy, flaking skin. These complaints increase with RH below 40%. We believe that the respiratory tract irritation which results from too low humidity, in combination with the recirculation of air, leads to an increase in respiratory illness. The increase may be as much as two to three times what would have occurred if the humidity had been in a better range and the addition of outside air had been appropriate. There are many examples in the literature which support the increased opportunity for infection inside buildings. Diseases not ordinarily communicable have been reported as epidemics in specialized buildings such as hospitals and laboratories.(3) Q fever has been spread through ventilation systems in buildings where sick animals are housed

or the organism is cultured. Tuberculosis was demonstrated to have spread in a factory far more aggressively than in the community around the factory (33% of all plant employees vs. 10.7% of the community, about three to one).(4) The building ventilation was considered to be responsible for the aggressive spread. The rate of transmission of respiratory disease in new, airtight, army barracks was shown to be elevated between 51% and 250% compared to old style barracks which were much more open and better ventilated.(5)

a. When humidity is low enough, irritated sinuses and bleeding mucous membranes are a problem. There is little doubt that a bleeding membrane is a less effective barrier to disease than an intact one. Combine this with increased exposure to infecting agents due to recirculation and it seems only reasonable to expect an increase in respiratory disease.

b. It is difficult to detect changes in illness rates in buildings by looking at absence rates. We made an effort to do this and found the task to be much more complicated than it appears. The days the federal government tracks as sick leave are in fact a combination of sick leave and other unscheduled days lost. The figure is really a gross absence rate and not just documented sick leave. Further, not all sick leave is taken as sick leave. Many persons build up compensation time and use it when they are sick. Others use annual leave instead of sick leave for a variety of reasons. As a result much time lost for illness is either not recorded in the formal system under any category at all or is recorded as annual leave. Even if we are able to obtain an accurate listing of sick days, for our present purposes it is necessary to subtract from that total those days used for illness which is obviously unrelated to the building in question. In most work situations we have reviewed, 60% to 65% of the total sick days are contributed by 10% to 12% of the population. We have been able to locate one study recently which gives similar figures.(23) These figures are not hard figures and will require further study to completely validate, but they are the best we can find to assist pragmatically in dealing with the problem at hand. The persons who generate the greatest number of sick days usually have very serious medical problems. The diseases are most unlikely to have been caused by building environment. If we remove these from the tally, the average number of sick days per person remaining declines to about 35% to 40% of the original average. In the case of the Federal Government this means that the nine days of sick leave per person per year would decline to about 3.5. This is a number which coincides with the Bureau of Labor Statistics reported national average figure for documented sick days and also coincides with the number we have found in problem-free buildings. In conducting building assessments we have made an effort to assess the number of days absent actually taken for illness. Because of limited manpower and time we were not able consistently to assess a statistically meaningful sample. Some of the buildings had 3000 occupants. Nonetheless, in buildings with problems we obtained total sick days that ranged from approximately 1.4 to 3.5 times expected with an average of 2.5. We do not have sufficient data to adequately correlate these numbers with building problems; however, the numbers are consistent with the published literature detailed above and complementary to the data in paragraph F below.

4. When dust levels are high and humidity low, skin problems are enhanced. The skin dries when the humidity is low. This decreases its resistance to irritating effects. If VDTs or other sources of static electricity are present, irritation of the skin, particularly of the face

around the eyes, is often a finding. This is severe at times. We have seen eyes swollen shut and skin weeping from this effect. The problem results from the dust settling on the skin or being propelled by static charge at the face or other body part and irritating the skin. Some people seem completely immune to this problem while others are more sensitive. Fair skinned females are most susceptible while dark skinned males are most resistant.

5. The inability to wear contact lenses in a dry building results from the loss of fluid from the surface of the eye to the too dry atmosphere. The loss of lubrication which results causes irritation and irritative conjunctivitis. This enhances the possibility of infection. Even without contact lenses the eyes burn, feel dry, irritated, and itchy. It is not difficult to understand the development of concern that chemicals are rampant in the environment. This belief generates more than a little concern. We have seen the chemical causation hypothesis enhanced by the fact that plants were dying in the office. The air was so dry that the plants were dying of thirst and salty soil. It was necessary to water so frequently that salts built up in the soil to the lethal level.

6. Inadequate balancing of ventilation systems often leads to marked variations in temperature over short distances in a building. Poor or no maintenance of equipment responsible for directing air flow often creates closed loops in systems which are unresponsive to central control. Worse, the temperature may vary so widely in the same location over short periods of time that the anticipation of the next cold blast after a hot period detracts from attention to work. All too frequently, little consideration is given to actual occupant and equipment load on the ventilating system. Temperature and odor then become problems. The tendency to increase the density of equipment and people is driven by the cost of space. This tactic leads to increased total costs per square foot of space because of increasing personnel per square foot. The cost is then translated to the occupants health and productivity with increasing inefficiency as the cost per square foot rises. Because of increased equipment density, heat load is often too great and adequate temperature control is lost. In these conditions the cost of a relatively cheap resource, energy, is translated to the cost of the most expensive resource, people. This is a no win situation.

F. In reference to the discussion in paragraph II D 6, it is fortunate that by increasing the amount of added outside air when it is inadequate we can improve health and productivity as well as save money. The following discussion is an economic analysis of energy conservation versus adequate fresh air. Annual energy, maintenance and personnel costs are discussed.

The cost of personnel in the Air Force averages about $250.00 per square foot per year. The maintenance and energy costs for all operations in a building rarely exceed $7.00 per square foot per year. Of the $7.00, no more than $2.00 are energy costs. If the unlikely proved true and we saved half of all energy costs by running closed or minimum fresh air cycles, that would be $1.00/sq ft/yr. This is the equivalent of seven hours per square foot of personnel time. This is less than two minutes per day per year. If only two minutes per day productive time is lost, then all energy savings are wiped out. Respiratory disease is at least 1.5 to 3 times more likely in a tight environment. Common respiratory infection episodes last eight to ten days with one to two days of absence being usual. The average number of respiratory infections involving colds and flu is one per person per year based on National Center for Health Statistics data. Tight buildings are likely to raise that number to between 1.5 and 3.0 episodes per person per year. Using the lower figure of one day of loss per episode, we have raised the lost days from one to between 1.5 and 3 per person per year with an average of 2.25 days. This is an average increase of 1.25 days. By this measure alone we have lost 10 hours, three more than is required to put us in the deficit column. Three of the days of infection are likely to suffer from reduced productivity by at least 20% for a total of 60% of a day. Cost is now 1.85 excess days lost; 1.85/220 = 0.84% x $250/sq ft/yr = $2.10/sq ft/yr. In terms of common colds and flu alone we have already lost $2.10/sq ft/yr. This cost already exceeds the savings possible by running the air handler with inadequate fresh air by 2.1 times. This analysis does not begin to address the losses due to aggravation of pre-existing problems such as asthma and allergies, the cost of other diseases known to result from improper maintenance and operation of air handlers, the loss in productivity due to irritant effects of poorly controlled "comfort" parameters or the losses due to the social atmosphere surrounding the problems generated. The actual savings from running closed cycle are even less than the generous $1.00 we allowed. It is usually necessary to increase total outside added air from roughly 10% to about 20% of total flow to obtain adequate fresh air and control CO_2 to appropriate levels. If all of the $2.00 were going to climate control, this represents only 20 cents rather than a dollar in savings. Since this is so, the actual relative loss from increase in infections is $2.10/0.20 = 10.5 times the possible energy savings if all energy is used for heating. This is a poor bargain.

III. CONCLUSIONS

The foregoing information demonstrates that, with increasing CO_2 levels there are increasing complaints, increased rates of respiratory illness, and loss of productivity which more than offsets energy savings. Available animal data indicate that the TLV for CO_2 is set too high at 5000 ppm. Studies on the physical and psychological effects of inadequate ventilation show clearly that noticable effects occur at very low levels of CO_2. We believe this information establishes that the present 1000 ppm CO_2 guideline for ventilation is not adequate to maintain health, productivity or general comfort. We believe the available information warrants setting a limit for CO_2 below the present 1000 ppm and maintaining humidity at higher levels than the current minimum recommendations. Other factors certainly have been the cause of building problems and specific recommendations for minimum periodic cleaning, filter changing and other routine maintenance of the air handler and duct system must be made to assure that microbial contamination, particulate levels and chemical content of the air meet adequate health and comfort standards. We make recommendations below regarding the levels of humidity and CO_2 that we believe are justified on the basis of present information. We believe they are justified on the basis that they use changes in human physiology as points for departure and seek to avoid such changes. We further believe the chance of disease occurring at these levels is small and justifies avoiding the expenditures that would be necessary to attain levels that would be required by the usual environmental risk assessment models. We emphasize that all standards whether ANSI, ASHRAE, ACGIH or government agency, are guidelines and not absolute values unsubject to change. Professional judgment must supersede any number that is proving to be inadequate. The ultimate baseline, as ASHRAE states, is human health and acceptability.

IV. RECOMMENDATIONS

A. Based on the foregoing we recommend that air handlers be designed to maintain CO_2 levels below 600 ppm as a ceiling, and humidity levels between 40% and 65%. We further recommend that the 80% building population satisfaction level set by ASHRAE in their standard be determined by survey within six months of initial building occupation, and annually thereafter to account for the many changes possible in a building in a year. We recommend the survey instrument be distributed by management and analyzed jointly by civil engineering and medical personnel. We have found the instrument at Appendix C useful for this purpose.

B. Design of new facilities or retrofitting older facilities should be based on a fresh air flow rate derived from the following equation;

$$G = \frac{216{,}000 \times n}{(600 - O) \times 28.3}$$

where G = fresh air flow rate (cfm)
n = number of people in building
O = average outside air CO_2 concentration in ppm

The minimum fresh air flow rate is 25 cfm and may be higher depending on the ambient CO_2 concentration. The derivation of this equation may be found in Appendix B.

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APPENDIX A

STATISTICAL ANALYSIS OF SURVEY DATA

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We performed statistical analysis on our data in two procedures. First, we combined the data from personal interviews conducted prior to the development of the questionnaire with the questionnaire data for complaints dealing with fatigue. Second, we performed an analysis of variation (ANOVA) on the questionnaire data. The latter method allowed us to look at more symptoms while the former allowed a larger data base for review.

All the data for fatigue and CO_2 were compiled into one file. This file took the form of percent complaints (fatigue) and corresponding CO_2 levels. We determined a theoretical model based on the following premise:

a. CO_2 exists naturally in the environment, therefore there is a no effect threshold (A).

b. There are some individuals that will not experience any noticeable effects from CO_2 at high levels, therefore, the complaint rate will never reach 100%.

c. There is a CO_2 equilibrium state between the body and the environment (K).

Based on these assumptions, the following equation can be derived:

$$\text{percent complaints} = 100(1-e^{(CO_2-A)K})$$

Using the SAS program NLIN, we iterated our observed data using the Gauss-Newton method. The iteration converged giving the following values:

no effect level = 470 ppm +/- 130 ppm (95%)
equilibrium constant = 0.0012 +/- 0.0005 (95%)

The second statistical analysis was performed on the questionnaire data only. Due to the relatively small data base, n = 201, the analysis would be weak, true effects would not be seen. Due to the lack of statistical power, we defined the effect level as $p < 0.05$ and a tendency as $.05 < p < .15$. The results of this analysis are presented in the text of this document.

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APPENDIX B

CALCULATION OF MINIMUM FRESH AIR FLOW

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1. There are several methods for determining the required building fresh air flow rate. In our medical judgment, based on the information contained in this monograph and its references, the method most suited to optimizing human health, productivity and comfort utilizes CO_2 production and normal respiratory rates.

2. The following assumptions are used in determining fresh air flow rates;

average respiratory rate = 6 liter/min
average CO_2 concentration in expired breath = 3.6% (36,000 ppm)
concentration of CO_2 in building in morning = concentration outdoors

$$\frac{\text{ul } CO_2}{\text{min person}} = 36{,}000 \text{ ppm} \times \frac{1 \text{ ul/L}}{\text{ppm}} \times \frac{6 \text{ L}}{\text{min person}} = \frac{216{,}000 \text{ ul } CO_2}{\text{min person}} = P$$

ul in building at time = 0 = Y

$$Y = CO_2 \text{ (outdoors)} \times \frac{1\text{ul/L}}{\text{ppm}} \times \text{Volume of building}$$

ul of CO_2 in fresh air = T where G = flow rate (L/min)

$$T = CO_2 \text{ outdoors} \times \frac{1\text{ul/L}}{\text{ppm}} \times G$$

The change in the CO_2, C' = CO_2 in building - CO_2 leaving the building

$$C'(t) = (P+T) - \frac{G}{V} \times C(t)$$

$$C(t) = \frac{(P+T) \times V}{G} + ce^{-(G/V) \times t} \quad \text{where c is a constant}$$

at t = 0

$$C(0) = \frac{(P + T) \times V}{G} + c$$

Therefore $c = C(0) - \frac{(P + T) \times V}{G}$

Finally

$$C(t) = \frac{(P + T) \times V}{G} \times (1 - e^{-(G/V) \times t}) + C(0) \times e^{-(G/V) \times t}$$

as G/V X t approach infinity e-(G/V) X t approach zero thus,

$$C(max) = \frac{(P + T) \times V}{G} = \text{ul } CO_2 \text{ in building}$$

to convert to ppm, divide C(max) by building volume V (liters)

$$ppm(max) = \frac{P + T}{G} = \frac{P}{G} + \frac{T}{G} \text{ and } T/G = \text{outside air } CO_2 \text{ in ppm}$$

or

$$ppm(max) = \frac{216{,}000 \times \#persons}{G \times 28.3} + CO_2 \text{ outside air where } G = CFM$$

APPENDIX C

QUESTIONNAIRE

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NAME____________________________ (optional) SEX M F AGE_____

BASE/CITY______________________ BUILDING______________________________

This questionnaire is being distributed to assess the satisfaction of building occupants with building conditions. Your cooperation in giving us accurate data is appreciated. Please answer the questions positively if you have any of the following symptoms or conditions and you believe they are caused or aggravated by the building environment. Place the number describing frequency next to the condition. Only one answer per question.

A. 0 - Never, 1. Sometimes, 2. Often, 3. Always

1. ___ Aching Joints
2. ___ Nasal irritation, sinus
3. ___ Back Pain
4. ___ Ear problems
5. ___ Eye irritation/itching
6. ___ Dizziness
7. ___ Dry, itchy skin/rash
8. ___ Headache
9. ___ Fatigue
10. ___ Drowsiness/sleepiness difficulty concentrating
11. ___ Shortness of breath
12. ___ Chest tightness
13. ___ Coughing
14. ___ Sneezing
15. ___ Wheezing
16. ___ Hayfever/allergies
17. ___ Colds
18. ___ Bronchitis
19. ___ Asthma
20. ___ Building too warm
21. ___ Building too cold
22. ___ Other (Please use other side if necessary)

B. When do these symptoms occur?

1. Morning 2. Afternoon 3. Night 4. All the time

C. Do the symptoms get worse as the week progresses?

1. Yes 2. No 3. Does not apply

D. When do you experience relief from these symptoms?

1. ____ Upon leaving the building
2. ____ When you get home
3. ____ On weekends only
4. ____ Only on extended absences (vacation etc.)

E. Do you smoke? 1. Yes 2. No If yes, how many packs per day? 1/2, 1, 2,

F. Where are you located in the building? Floor ______ Wing/Area _____

G. Are you near office equipment? If so, what type?________________________

H. Any other comments you wish to make may be written on the reverse.

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